University of Idaho
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ECE 528 – Understanding Power Quality

http://www.ece.uidaho.edu/ee/power/ECE528/

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Lecture 28

Today…

- Midterm exam questions
- Capacitors
  - Utility and end-user capacitor applications
    - Overview
    - Capacitor sizing
    - Current reduction
    - Loss reduction
    - Location discussion
    - Power factor charges
    - Voltage rise

Capacitors - overview

- A local reactive power source, that can improve power factor and in turn…
  - Reduce real power losses
  - Release transformer and conductor capacity
  - Reduce power factor charges
  - Boost voltage

Power factor: Displacement, True, and Distortion

- (from lecture 19)
  - Displacement power factor - fundamental only

$$\mathrm{DPF} = \cos\theta$$

  - True Power Factor – includes harmonics

$$\mathrm{PF} = \frac{P}{S} = \frac{\mathrm{Active\_power}}{\mathrm{Apparent\_power}}$$

True Power Factor may also be called “Power Factor” or “Total Power Factor”

Power factor:
Displacement, True, and Distortion

- Distortion PF: Relates RMS of the distorted current, including the fundamental current, to RMS of the fundamental current only

$$PF_{dist} = \frac{1}{\sqrt{1 + THD_I^2}}$$

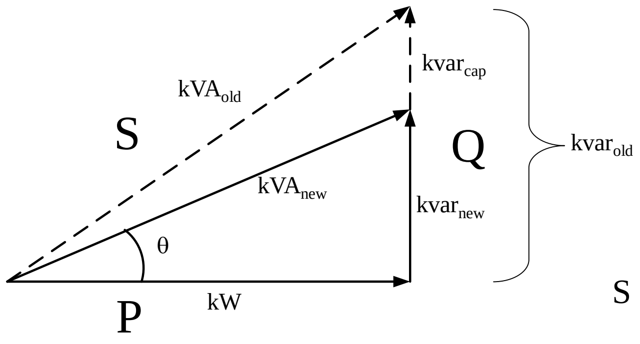
- How displacement, distortion, and true power factor are related

$$TruePF = DPF \; x \; PF_{dist}$$

- Adding capacitors only corrects DPF. This equation shows that the best TPF we can achieve by adding capacitors is limited by the distortion power factor.

Sizing capacitor banks

- To correct Displacement PF, analyze the power triangle



$$\cos(\theta) = DPF$$

$$P = S\cdot\cos(\theta)$$

$$Q = P\cdot\tan(\theta)$$

$$S = \sqrt{P^2 + Q^2}$$

$$S = \frac{P}{PF} \qquad PF = \frac{P}{S}$$

Reminder – the “Power Factor Teaching Tool” Excel spreadsheet is on the class website.

Sizing capacitor banks

- Text equations: (PSQ pg. 342 has an error)

$$\mathrm{kVAR} = \mathrm{kW}\cdot\left(\sqrt{\frac{1}{\mathrm{DPF_{orig}}^2} - 1} - \sqrt{\frac{1}{\mathrm{DPF_{new}}^2} - 1}\right.$$

$$\mathrm{kVAR} = \mathrm{kW}\cdot\left(\tan\left(\theta_{orig}\right) - \tan\left(\theta_{new}\right)\right)$$

These equations can be used if we know the real power, the existing power factor, and our target power factor.

Sizing capacitor banks

- Some other useful equations

$$Q_{old} = P\cdot\tan\left(\mathrm{acos}\left(\mathrm{DPF_{old}}\right)\right)$$

$$Q_{old} - Q_{cap} = Q_{new}$$

$$\mathrm{DPF_{new}} = \cos\left(\mathrm{atan}\left(\frac{Q_{new}}{P}\right)\right)$$

These equations can be used to find the reactive power for a given power factor and the new power factor when a capacitor is installed.

Line current reduction

- Line current reduction is approximately*:

$$\%\Delta I = 100\left[1-\left(\frac{\cos\theta_{before}}{\cos\theta_{after}}\right)\right] \qquad \%\Delta I = 100\left[1-\left(\frac{DPF_{original}}{DPF_{corrected}}\right)\right]$$

Apparent power can also be used to calculate current:

$$I = \frac{S_{3\_phase}}{V_{LL}\cdot\sqrt{3}}$$

A *change* in S can be used to calculate a change in current.

*assumes voltage at the load doesn't change.

Loss reduction

- The reduction in system losses is approximately:

$$\%loss_{reduction} = 100\left[1-\left(\frac{DPF_{original}}{DPF_{corrected}}\right)^2\right]$$

- The portion of the original losses remaining after power factor correction is approximately:

$$\%\,power\,loss \propto 100\left(\frac{DPF_{original}}{DPF_{corrected}}\right)^2$$

Why install capacitors

- Release conductor and transformer capacity
  - Reducing current in conductors and transformers makes additional capacity available in those conductors and transformers
- Reduce real-power losses
  - Reducing reactive power flow *through* conductors and transformers reduces real power losses (I^2R losses) *in* conductors and transformers

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Capacitor location considerations

- Capacitors do NOT change the power factor of the load
- They are a local source of reactive power for inductive loads
- This distinction is important and can be used as a guide when deciding where to install capacitors

Capacitor location considerations

- Current and the associated losses are only reduced <u>upstream</u> of the capacitor
- Installing a capacitor near, but downstream of the service meter reduces power factor charges if there are any, but does not address losses inside the facility

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Capacitor location considerations

- Ideally, capacitors should be placed as close as possible to the location where reactive power is needed
  - May be switched with specific motors*
- Trade-offs
  - Multiple small capacitors may be more expensive than one larger one
  - It may be easier to control harmonics in one location

*Beware of self-excitation risk

Capacitor location considerations
Self-excitation

- If a motor with terminal-connected capacitors is isolated, the capacitors can provide a path for reactive power flow back and forth between the motor and capacitor.
- Voltage at motor terminals can increase to damaging levels.
- If motor and capacitor are reconnected to system, phase shift may be large, resulting in transients in voltage, current, and torque.
- To reduce likelihood of self-excitation:
  - Limit capacitor bank to 20 to 30% of motor kVA [1]
  - Limit capacitor bank to motor's magnetizing kVA[1]

$$Q_c \leq 0.9 \cdot I_{no\_load} \cdot V_{line} \cdot \sqrt{3}$$ [2]

Capacitors and power factor charges

- Power factor charges

  A popular method of charging for poor power factor is to adjust the customer's demand charge based on the difference between a target DPF and the customer's actual DPF when the customer's DPF is below the target

  Examples:

$$Adjusted\,Demand = Demand((0.97 - DPF) + 1)$$

$$Adjusted\,Demand = Demand\left(\frac{0.90}{DPF}\right)$$

More on capacitor size and location

- It's important to understand the applicable rate schedule before installing capacitors
  - You can't save money you're not spending in the first place
- A large capacitor bank may cause large voltage changes when switched on or off

Voltage improvement – Primary system

$$\Delta V = \frac{Qcap\_3\phi}{MVAsc\_3\phi} = \frac{Xs}{Xc}$$

(in per-unit),
Q is in MVAR

$$\frac{kV_{LL}^{2}}{X_S(\Omega)} = MVA_{sc\_3\phi}$$

(in MVA)

Given a capacitor bank size in kVAR and the system short circuit MVA or the system voltage and upstream impedance in ohms at the capacitor's location, we can calculate the per-unit or percent voltage rise.

Voltage improvement – Secondary system

- Voltage rise is approximately:

$$\% \Delta V = \frac{kvar_{cap} x \, Z_{tx}(\%)}{kVA_{tx}}$$

  - Assumes system impedance is dominated by the transformer
    - Example:
      Capacitor: 300kvar
      Transformer: 1000kVA, 6% impedance
      Voltage rise (%)?

Next time…

- Finish Ch. 7
  - Flicker
  - More examples

References for self excitation:

[1] EPRI Power Plant Electrical Reference Series, Volume 6 – "Motors"

[2] Wiki-Electrical Installation Guide, "Power Factor Correction of Induction Motors"

http://www.electrical-installation.org/wiki/Power_factor_correction_of_induction_motors